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13. ABSTRACT *(Maximum 200 Words)*
This report outlines the focus of the development of advanced adaptive optics at the University of Arizona, Steward Observatory's Center for Astronomical Adaptive Optics (CAAO). The main focus of the development effort has been the design and development of the world's first adaptive secondary and control system for the 6.5 m MMT facility in Southern Arizona. The system is now undergoing extensive testing at the Steward Observatory Mirror Laboratory prior to integration with the MMT in the Fall of 2001.

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REPORT TO THE
AIR FORCE OFFICE of SCIENTIFIC RESEARCH

SUMMARY OF WORK FROM May 1, 1997 THROUGH April 1, 2001

Center for Astronomical Adaptive Optics (CAAO)
Steward Observatory, University of Arizona

Sponsored under Grants F49620-96-1-0366, F49620-99-1-0285, and F49620-1-0294

19 April 2001

Table of Contents

1. Introduction

The Center for Astronomical Adaptive Optics has as its mission the development of techniques for high-resolution imaging and spectroscopy on the new generation of large ground based telescopes. Both DOD and civilian astronomical communities benefit from the advances made. This report serves as the final technical and progress report for the AFOSR Grants **F49620-96-1-0366, F49620-99-1-0285, and F49620-1-0294**. This report describes the work that has been conducted during the course of these grants, with the main emphasis on the primary effort, the construction of a powerful new kind of adaptive optics system, using an adaptive secondary mirror and a sodium laser guide beacon for the Multiple Mirror Telescope facility. The system will shortly be installed at the 6.5 m telescope recently refurbished by the University of Arizona and the Smithsonian Institution. The telescope is nearing the end of the conversion process on Mt. Hopkins in southern Arizona, and when operated with adaptive optics, will become a unique and state-of-the-art tool for imaging with unprecedented quality and clarity.

2. Status of the 6.5m Telescope

The new telescope uses a 6.5 m diameter spin-cast borosilicate primary mirror, cast and polished in the Steward Observatory Mirror Lab. The installation of the telescope is complete -- the mirror cell was put in place on August 6, 1998 and the primary mirror was successfully installed on March 25, 1999. The first fixed secondary mirror was installed in the telescope in early May 2000. First light at Cassegrain focus was achieved on May 17, 2000. The image quality exceeded all expectations. The telescope was dedicated on May 20, 2000.

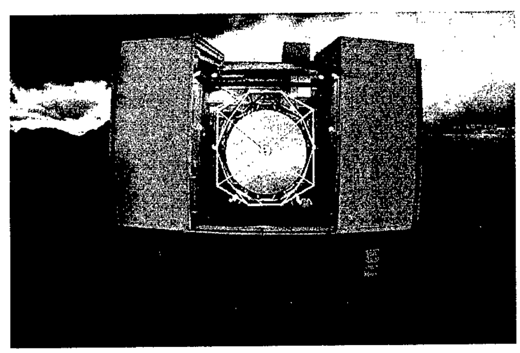

Figure 1: The 6.5m MMT Facility

At the present time, work continues on characterizing the active primary mirror supports, and to implement the active mirror cooling system. The facility is now conducting scientific operations and is preparing for the integration of the adaptive secondary in Fall 2001.

3. Overview of the 6.5m Adaptive Optics System

The block diagram of the MMT AO system is shown in Figure 2. The major building blocks are the following:

- Deformable secondary mirror with local electronics securing quick and stable deformation control;
- Top Box containing all the necessary optics, electronics and mechanical actions for fast and reliable wave-front sensing;
- Wave-front (reconstructor) computer, a custom built hardware and software for high speed matrix operations;
- Laser beam projector system to generate an artificial "star" in the Na layer of the atmosphere;

- ARIES science instrument, including a high-resolution imager, spectrograph, and an additional IR camera (the IR tip-tilt sensor) to detect the global tilt of the incoming beam.

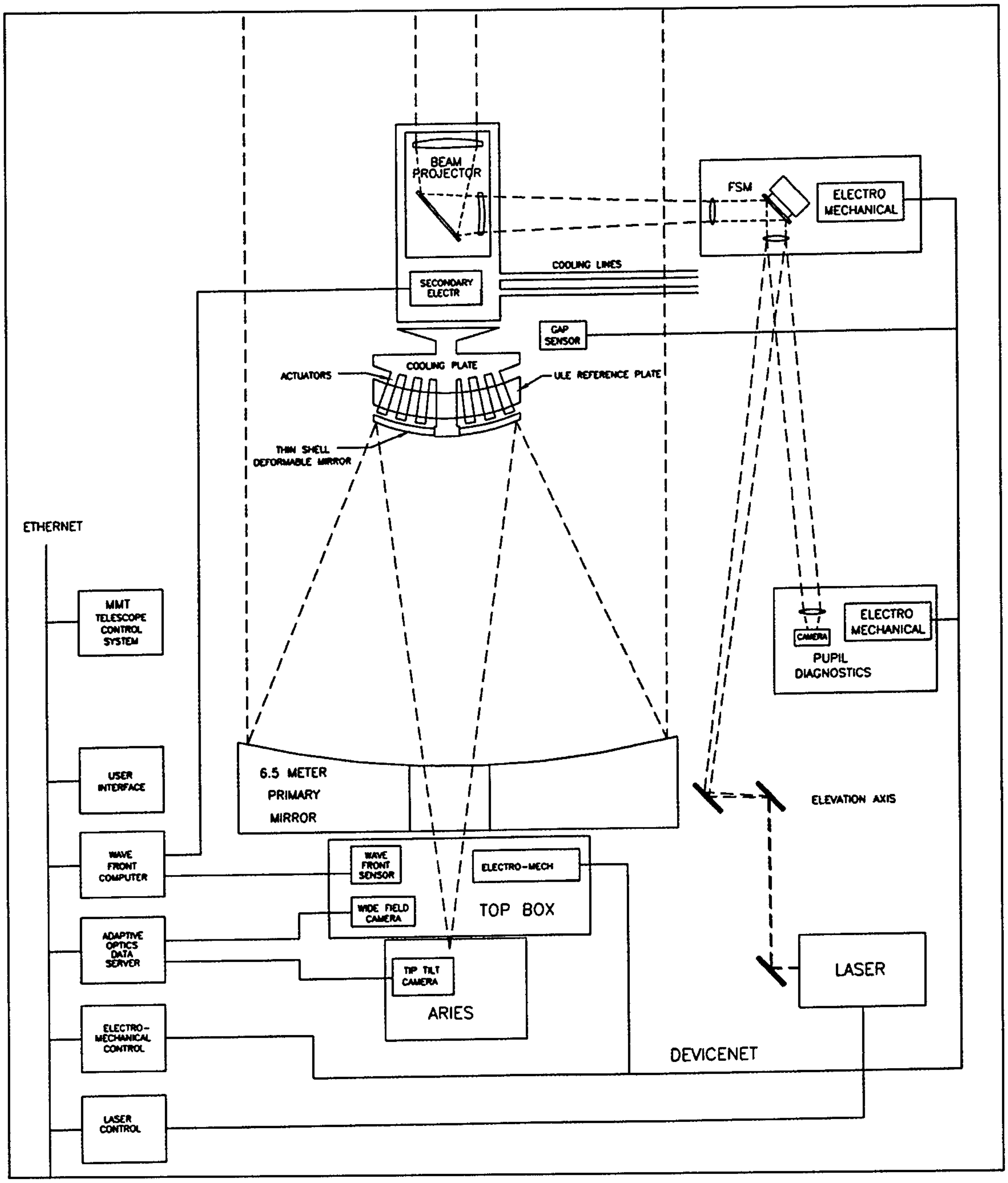

Figure 2: The block diagram of the MMT adaptive optics system as it will be when fully implemented

After reflection from the primary mirror, aberrations in the infrared wavefront are corrected at the deformable secondary, and the compensated beam is reflected to the Cassegrain focus. Here, a dichroic beamsplitter allows infrared light > 1 micron to pass into the ARIES high-resolution infrared imager and echelle spectrograph. Visible light is reflected upward into the so-called "top box". This contains all the optics and detectors for measuring the instantaneous wavefront distortion. Readout from the wavefront sensor is used by a fast matrix multiplier hosted in a VME rack to compute corrections to the secondary mirror actuators

4. Subsystems Status

Construction of the adaptive optics system for the 6.5 m MMT conversion telescope was and remains the major focus of effort by the CAAO team. We summarize here the current state of the project at the end of the grant funding cycle. Four main components comprise the AO system:

1) Deformable Mirror;

2) Top Box which houses the wave-front sensor (WFS);

3) Wave-front reconstructor computer;

4) Tip/Tilt science instrument (ARIES).

The WFS and associated optics measure the optical distortion imposed by the atmosphere. Output from the WFS is read by the reconstructor computer which then derives and sends commands to the deformable secondary mirror to make appropriate corrections. Finally, ARIES, which is interfaced to the Top Box, records the high resolution images and spectra possible with the corrected telescope.

With AFOSR funding, the system construction phase at Steward Observatory in Tucson and Media Lario in Milan is completed. Presently, all of the major subsystems are being tested at Steward Observatory

4.1 Description of the Adaptive Secondary Mirror System

A critical advance has been the development of manufacturing methods for the very steep convex asphere of the secondary to very high optical quality, and yet only 2 mm thick. This has required new technology, developed at Steward Observatory Mirror Lab with support from this AFOSR grant, and now extended by us in a program to develop large very light weight mirrors for space-based applications.

The MMT AO system is the first to take advantage of the high photon efficiency and very low thermal background offered by an adaptive secondary mirror, seen in an exploded schematic view in figure 3. Figure 4 shows a photograph of the secondary in the lab in Tucson. Figure 5 shows the excellent figure of the fully corrected optical surface. The mirror has very recently been installed in the final optical system, and its performance has been tested by commanding its actuators to follow a simulated wavefront aberrated by Kolmogorov turbulence. The result for a single actuator is shown in figure 6. The commanded position is plotted together with the residual error - the difference between the commanded position and the achieved position, as measured by the internal capacitive sensors that monitor the mirror's shape at 40 kHz.

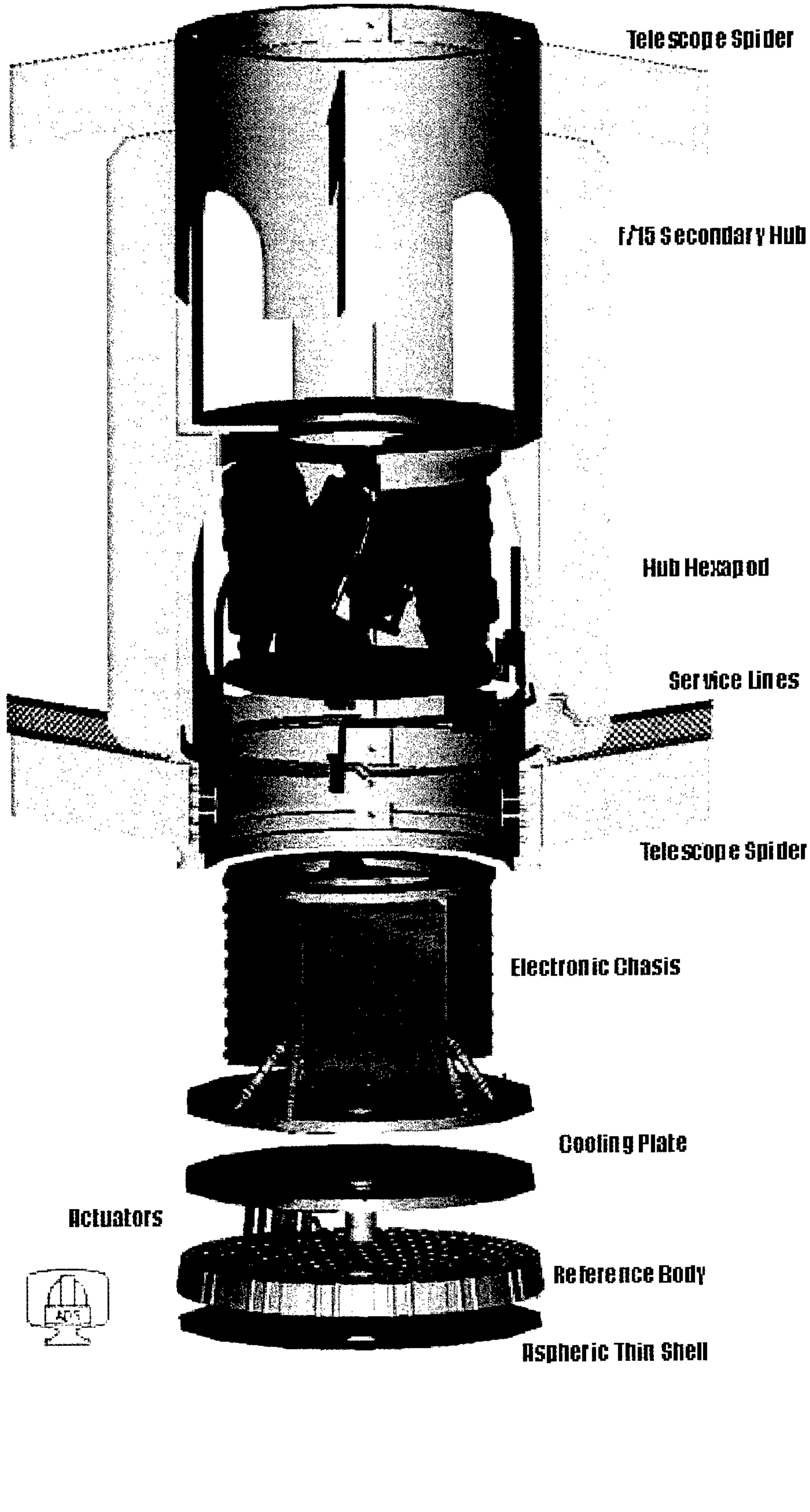

Figure 3: Anatomy of the deformable secondary

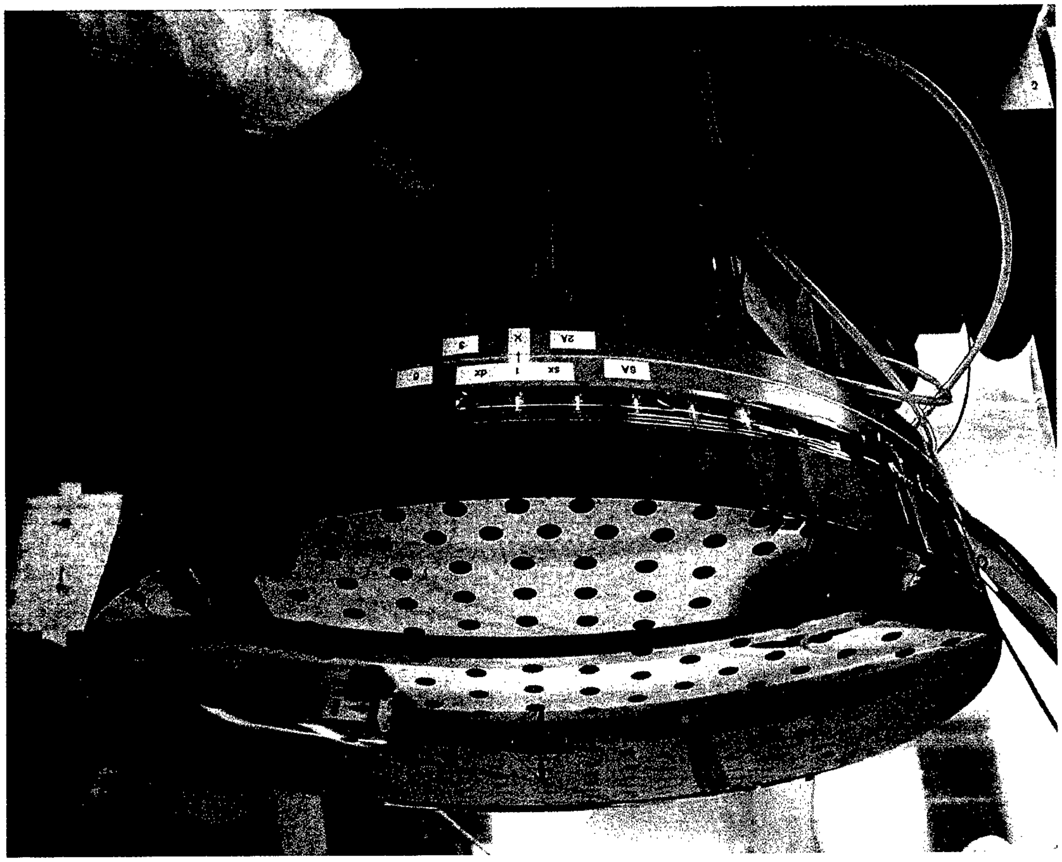

Figure 4: Photograph of the first adaptive secondary, intended for the 6.5 m MMT telescope. The front surface had not yet been aluminized, so the 336 actuators are visible as dark circles through the thin deformable shell

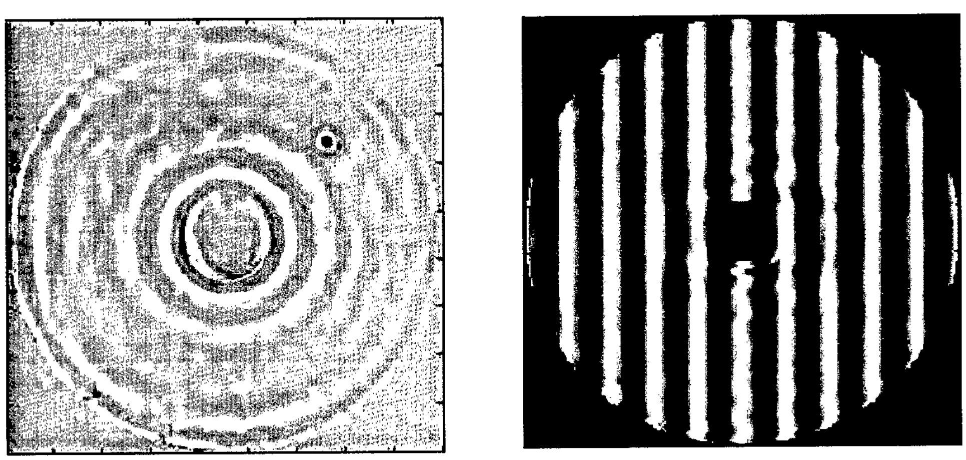

Figure 5: Computed residual error after corrections from applied 336 actuators at 30 mm spacing. The Left image shows 8 nm rms surface quality. The Image on the right is a synthetic interferogram at 633 nm

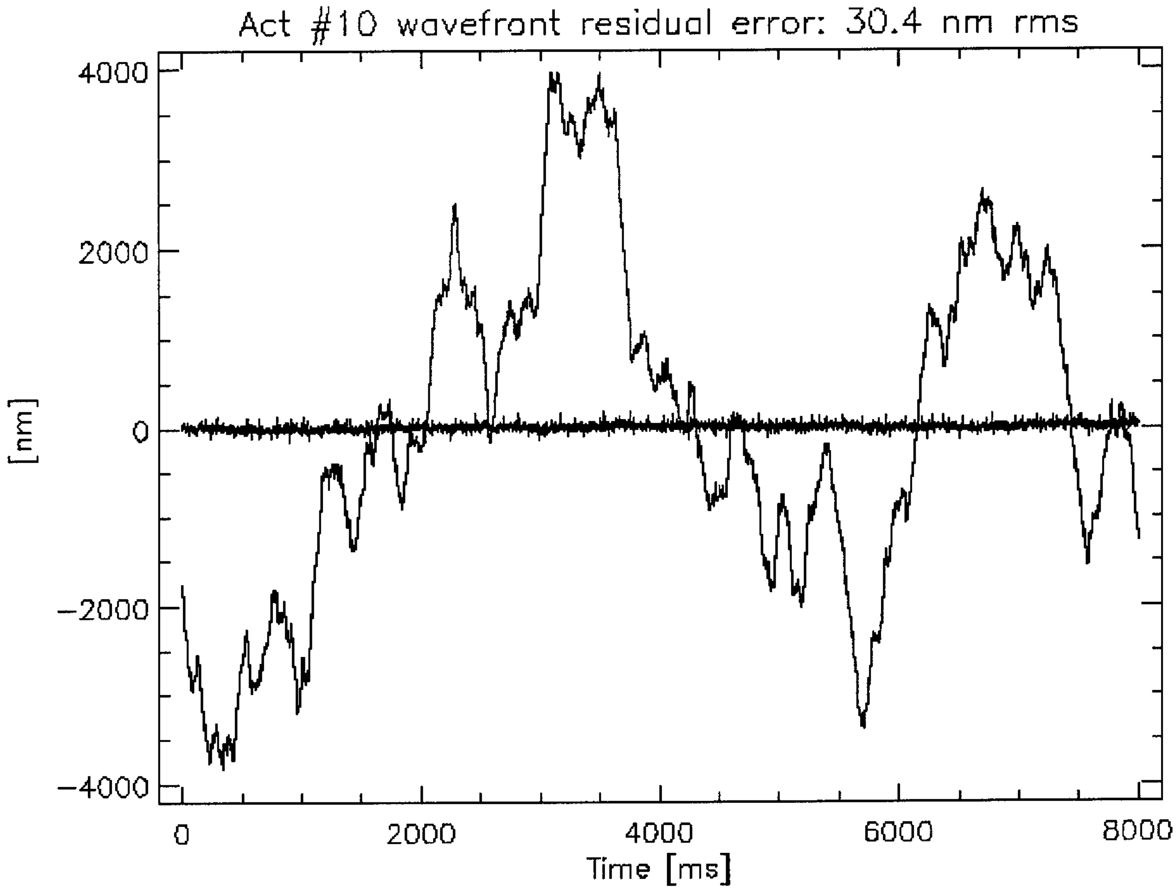

Figure 6: Performance of the adaptive secondary mirror when commanded to follow a simulated Kolmogorov wavefront

4.2 The Wave-front Sensor and Top Box

In 2000, the top box underwent a significant transformation. The prototype aluminum optical table was removed and replaced with a much stronger, stiffened cast aluminum plate. With the increased strength gravity induced flexure is dramatically reduced. The optical table design accommodate the 4 infrared instruments envisaged to be mounted at the Cassegrain focus of the 6.5 m telescope: 1) ARIES; 2) MIRAC, a K-band, L-band, and 10 μm imager; 3) BLINC, a 10μm nulling interferometer; 4) IRIS, a 10-18 μm imaging spectrograph.

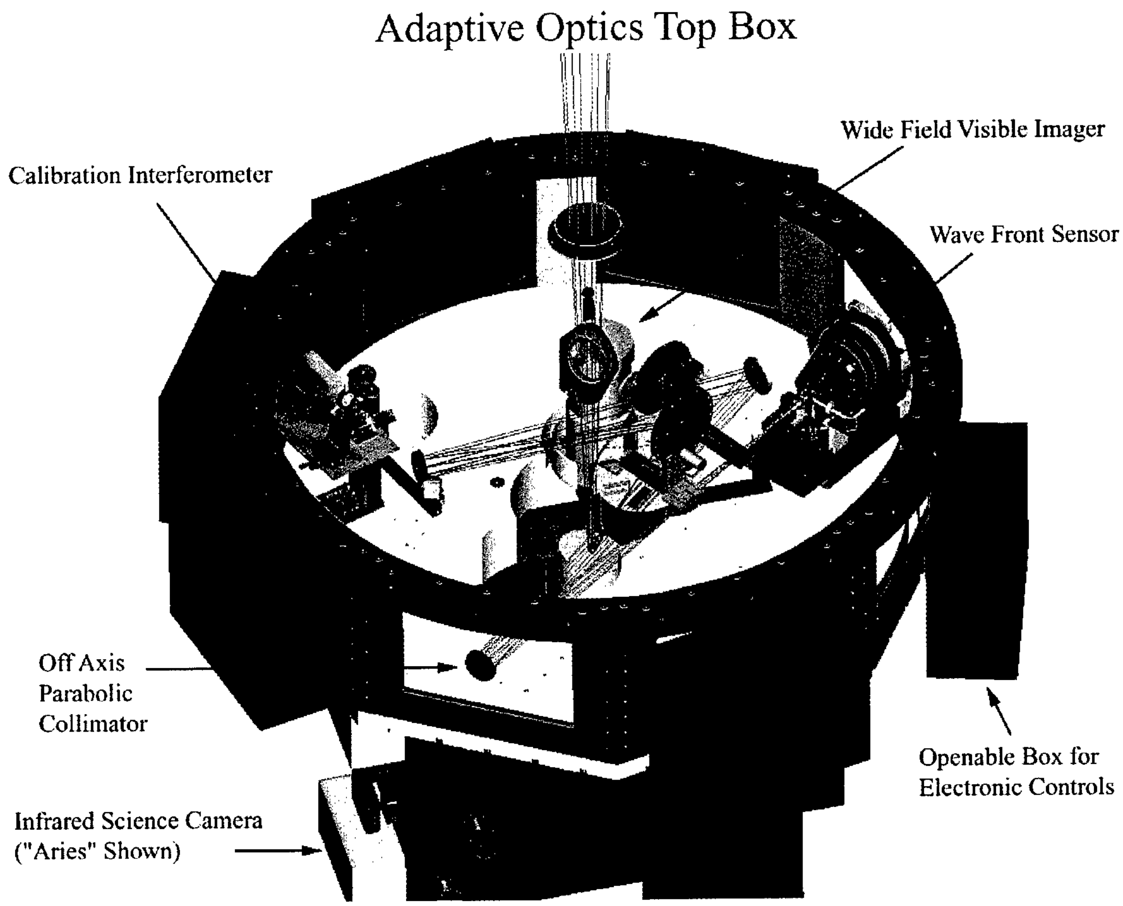

Figure 7: AO System Top Box

The wave front sensing optics have been fitted and aligned including the wavefront sensor (WFS). The assembly, alignment, and testing of the visible light wavefront shifting interferometer (PSI) used to characterize the wave front injected in the wave front sensing optics was completed in the fall of 2000. The PSI enables characterization of the visible wavefront downstream of the turbulence generator plates prior to interaction with the deformable secondary mirror. These measurements have established that the equivalent r_0 of a single turbulence generator plate is 0.24m.

Initially, a solid spherical secondary mirror was used to align and characterize the top-box and the test bench. In the fall of 2000, the aspherical thin shell (the aspherical thin shell will be the optical surface of the adaptive secondary) was installed in the prototype optics bench while still on its manufacturing blocking body. In the Fall and Winter of 2000-2001, the complete system was re-aligned. This step was critical in verifying the optical set-up in the "on-telescope" configuration" and our ability to properly align the system.

Considerable effort has been applied in acquiring a thorough comprehension of the test set-up alignment, in order to illuminate the WFS with a clean wavefront.

A wavefront reconstuctor using 100 Zernike polynomials has been built to produce an estimation of the phase from the wave front sensor raw signal. This phase has been compared to the phase measured by the interferometer, in 3 cases: no turbulence plate, one and two turbulence plates in the beam. The results are presented in the following table.

Table 1: Phase Measurement of Wavefronts

Phase Measurement	No turbulence plate [nm rms]	1 turbulence plate [nm rms]	2 turbulence plates [nm rms]
PSI	490	550	700
WFS	620	690	770
Phase difference (WFS - PSI)	230	270	370

Clearly, in an ideal case we would expect the phase measured by the 2 wavefront sensing to be equal. The difference is due to some non-common path aberrations (the WFS beam undergoes 5 reflections after the beam feeding the PSI is extracted) and in particular a pupil magnification error. This error is not a concern for the Adaptive Optics system because the PSI is not part of it and the important magnification is the one between the adaptive secondary and the wavefront sensor. Additional errors are due to small-scale aberrations beyond the bandwidth of the wavefront sensor. These aberrations are generated by multiple optical components, in particular the hologram used to shape the reference wavefront when it enters the test bench, the turbulence plates and the dummy secondary mirror used so far.

4.3 Infrared Tip/Tilt Cassegrain Science Instrument

With the 6.5 m adaptive optics system, the new MMT telescope is expected to resolve diffraction limited images (greater than 80% Strehl ratio at 2.2 μm), approximately an order of magnitude better than present seeing. This improved seeing capability along with the larger light collecting area and low thermal background required a new science instrument, diffraction limited for the 1 to 5 μm region. This science instrument, the Arizona Infrared Imager and Echelle Spectrograph (ARIES), is near completion and will rapidly transition to a preliminary lab test phase. ARIES consists of four cameras (optimized for plate scales from 0.019 arcsec/pixel to 0.102 arcsec/pixel), low resolution spectroscopy with grisms ($\lambda/\Delta\lambda$ from 250 to 500), high resolution spectroscopy with a cross-dispersed Echelle grating ($\lambda/\Delta\lambda$ from 3,000 to 60,000) and an atmospheric dispersion corrector. The cameras will provide simultaneous slit viewing, differential imaging and two pixel sampling over the full wavelength band. Each

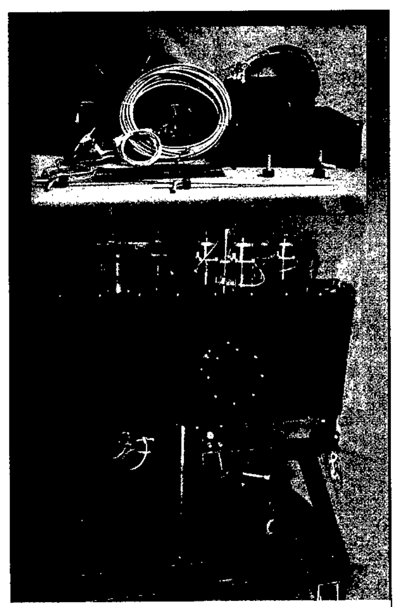

Figure 8: Completed ARIES science instrument

camera will operate with a 1024x1024 HgCdTe array optimized for the spectral region of the camera. An infrared tip/tilt sensor is also incorporated into the instrument that will relay natural guide star motion to the adaptive secondary in a closed-loop approach.

4.4 Status of the Sodium guide-star laser and projector system

The 6.5 m AO system is designed to work with a laser guide star. Optics and hardware for the launch telescope for a sodium laser beacon have been fabricated and await installation on the telescope. A selection for the laser itself has not yet been made. In common with the entire AO community, we have found great difficulty in obtaining quotes from industrial laser manufacturers for a laser that meets the demanded specifications. At present, the best option is an offer from EOST Inc, to build the laser at a cost of $1M, payable only on delivery of a tested system. A decision on whether to proceed with this purchase is expected at the end of 2001.

4.5 Status of Software Development

We identified three areas of software development that required significant attention: 1) Control algorithms; 2) AO System modeling; 3) Post-detection processing of AO images and information.

We launched and completed an aggressive effort in this direction. It has been the experience of many observatories that have undertaken implementation of AO systems that the required level of effort in software development is greatly underestimated, resulting in system commissioning. Our own experience with two previous prototype AO instruments at the MMT gave us an excellent understanding of the software requirements.

The development of the control algorithms that take advantage of the explicit knowledge of the shape of the deformable secondary was a considerable task. With our AO design, the adaptive mirror has more mechanical degrees of freedom than are measured by the WFS. The control algorithms if not supplemented by additional information describing the mirror shape would result in an unstable system. This significant hurdle was overcome by the addition of capacitive sensors associated with each actuator on the mirror. The combination of the control algorithms and capacitive sensors have allowed us to address the practicalities of controlling modes of oscillation not sensed by the WFS.

The second software task was to develop a model of the high resolution AO system. Seeing has been measured extensively at a number of telescope sites around Tucson in previous work, but there no standard mechanism in place to interpret the data and derive the required system parameters. This was particularly important given the innovations being incorporated into the high resolution concept, such as the multiple Rayleigh beacons, which have not previously been tested in practice. That need has now been filled by software packages that model the behavior of the 6.5 m AO system, and atmosphere above the telescope.

Finally, there was an imminent and very real need to extract accurate photometry and astrometry from images obtained with the MMT using AO. The requirements were to implement an astronomer-friendly package for post-detection processing of AO images which deals with data of variable SNR, and in which the PSF is not constant across the field. Without such a package of software, physical interpretation of compensated images is extremely difficult. This proved a challenge, which the AO community as a whole continues to tackle.

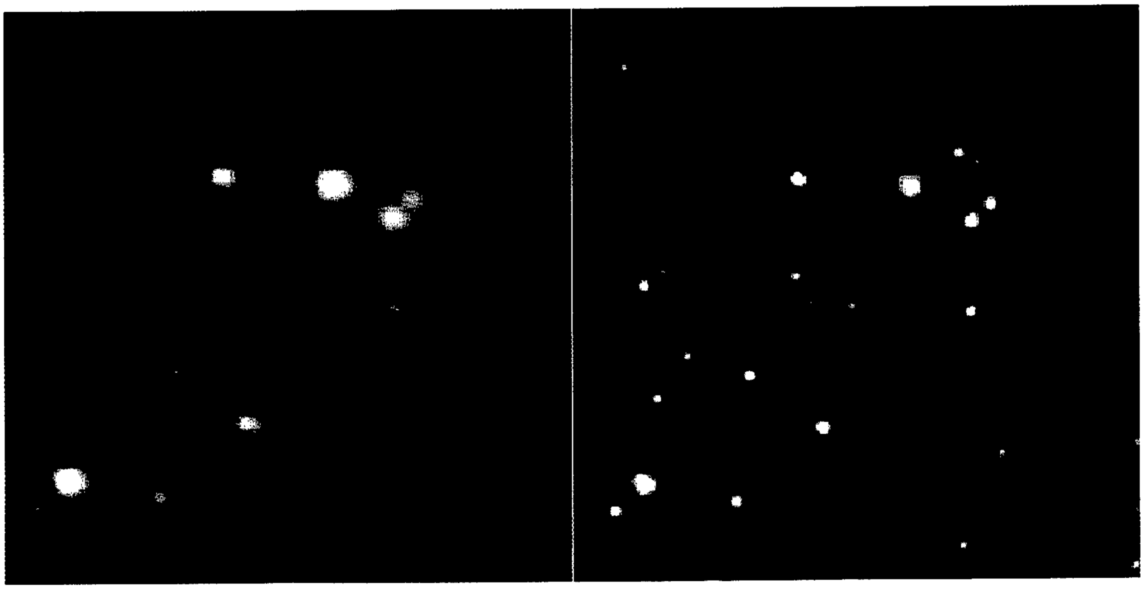

Figure 9: Two images of the center of globular cluster M13. Left - with adaptive optics at the MMT. Right - after post-processing with the PSFCAL software developed at CAAO. To verify that the software does not introduce artefacts into the data, the processed image has been compred with images of the same region recorded by the Hubble Space Telescope.

Our efforts continue in the development of such a package based on a powerful non-linear gradient descent algorithm which independently estimates the form of the illuminating object in the sky, and the point-spread function of the telescope optics and residual uncorrected atmospheric errors. Figure 9 shows the result of this post-processing on an image of the globular cluster M13, originally recorded at the MMT using adaptive optics with a sodium laser beacon. The AO system has already sharpened the image, but the computer processing further separates the star images, revealing many more faint objects that are then amenable to study.

5. Adaptive optics system integration and testing

In a critical test, the WFS subassembly was taken to the MMT and installed at the prime focus of the unfinished telescope. There, it has recorded data on the real atmospheric turbulence to be expected when the AO system is in full operation. In addition to the wave-front data collected, the test has demonstrated the coordinated functionality of two of the three critical components - the WFS itself, and the real-time control computer used to drive it and record the data.

5.1 Dynamic control of subscale mirror prototype

To demonstrate all the key features of the adaptive secondary, many of which are novel, and to develop expertise in the required construction techniques, a prototype adaptive secondary mirror with 36 actuators (P36) was constructed. The most critical result from the P36 testing has been to establish the algorithm needed to move the glass very rapidly.

This must be done under exquisite control, at the level of a small fraction of a wavelength of light.

The natural tendency of the continuous glass sheet to resonate uncontrollably is removed by passive viscous damping provided by a 40 micron layer of air trapped between the back of the shell and an adjacent thick reference body, carefully shaped to match the curvature of the shell. The P36 prototype showed the need for a fully dynamic control algorithm is not required, allowing a pseudo-static approach. A standard PID servo controller with force feed forward is used to position each of the 336 actuators.

5.2 Implementation Schedule

The schedule in Table 2 indicates the latest estimation for implementation and testing of the adaptive optics system at Steward Observatory and the 6.5m MMT facility in Fall 2001.

Table 2: AO System implementation on the 6.5m telescope

			1st Quarter			2nd Quarter			3rd Quarter			4th
ID	Task Name	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct
1	Aspherical Integration and Test @ Steward											
2	Mirror Lab System Integration and Testing											
3	MMT Integration Preparation											
4	MMT Integration											
5	MMT Testing											
6												

6. Advanced Concepts Research

6.1 High Density AO System for Visible-Light Compensation.

The adaptive optics system described in Section 4 will provide wavefront compensation to the diffraction limit of resolution in the near infrared. There is however much valuable science to be done at shorter wavelengths, in the visible. In addition, military applications of the system, such as high-resolution satellite imaging, and potentially power beaming experiments, would be greatly enhanced by a visible-light. capability. To that end, a program is underway to develop an inexpensive AO system with 10,000 controllable elements which will extend diffraction-limited imaging to below 500 nm.

The approach is to use this high density system (HDS) as a second stage of wavefront compensation after the adaptive secondary. Since the secondary removes all large scale aberration, the HDS is left to clean up high frequency wavefront errors which have small amplitude. The mirror actuators are therefore not required to have more than 2 microns of stroke, and this is the key to the low cost.

The wave-front corrector for the HDS is a128x128 liquid crystal array, providing about 10,000 correcting elements over the circular illuminated region. The wave-front sensor is a Mach-Zehnder interferometer, which measures phase directly within the small range of phase errors (80 nm rms) remaining after correction by the adaptive secondary. Because the two outputs of the interferometer can be combined electronically to give a direct measurment of the phase aberration, no digital reconstructor computer is required. The WFS output can be hard-wired to the liquid crystal phase corrector. This allows very fast operation of the HDS, and further reduces cost.

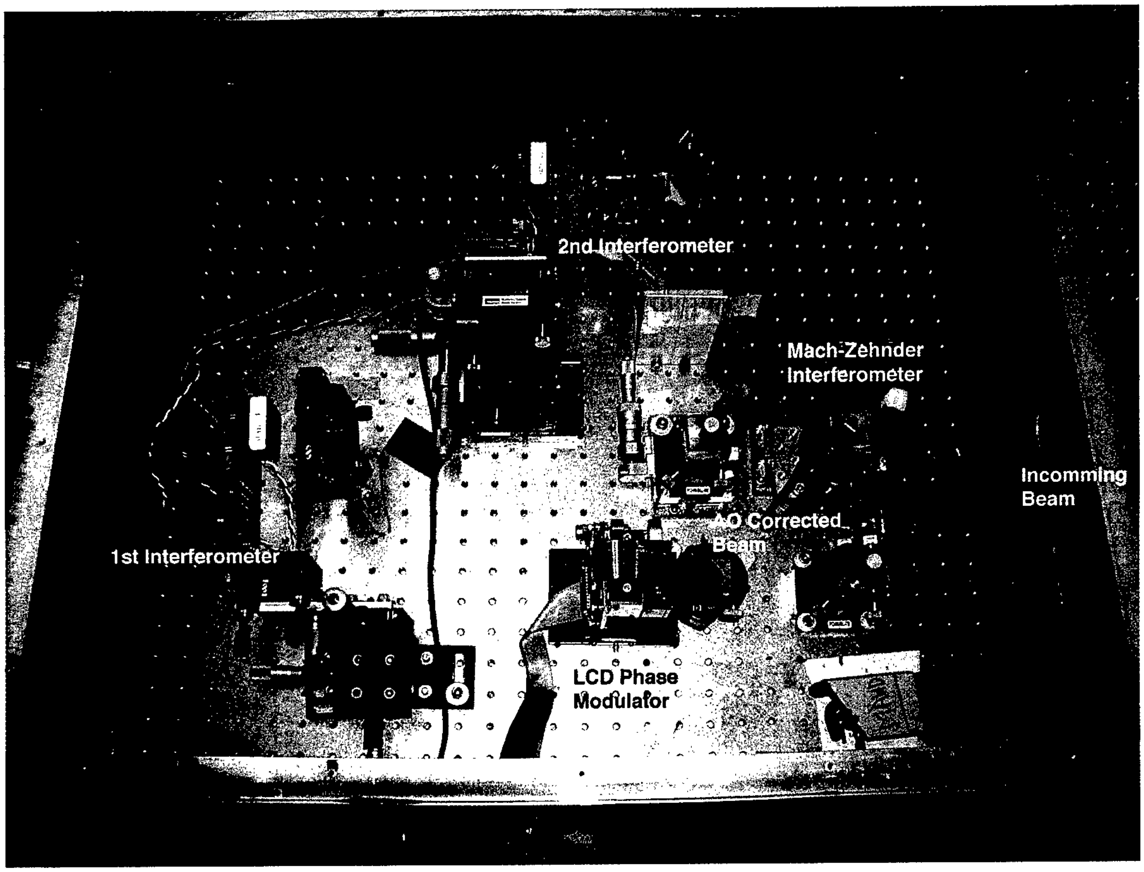

Figure 10: High density AO system for visible light compensation bench-top prototype

A prototype system has been constructed in the lab (figure 10). Initial open-loop experiments with this system have demonstrated the feasability of the reconstructorless AO system, and final full-speed closed loop tests are planned for April 2001.

6.2 Tomography with Multiple Rayleigh Guide Stars

We have proposed a new method for using Rayleigh laser guide stars to measure the 3-dimensional structure of the atmospheric turbulence above the telescope. Such measurements would open the way for multi-conjugate AO systems that would enormously increase the corrected field-of-view of a telescope. In this technique, a constellation of laser beacons would be created using pulsed UV lasers at around 350 nm. Wavefront measurements recorded from these beacons would be analyzed in real time to provide a tomographic view of the atmosphere.

A key feature of the technique is an opto-mechanical mechanism placed in the focal plane of the telescope that moves very rapidly to maintain focus on the pulses of laser light as they are flying away from the telescope at the speed of light. This allows much longer integration times than has hitherto been possible with Rayleigh beacons, so that bright beacons can be created with relatively cheap low power lasers.

Work has begun on the implementation of a single laser demonstration unit at the MMT. The dynamic refocusing mechanism, constructed as a double ring of titanium, is shown in figure 11. The demonstrator is expected to be operational by late summer 2001. In parallel, software is being written to perform the real-time tomographic analysis. Using a model of the atmosphere above Mt. Hopkins, we have shown (figure 12) that a ring of five laser beacons is sufficient to provide a field of view corrected to the diffraction limit of at least 2 arcminutes in diameter. For the near infrared, this provides a patch at least an order of magnitude larger than is expected with an AO system using a natural or single laser guide star.

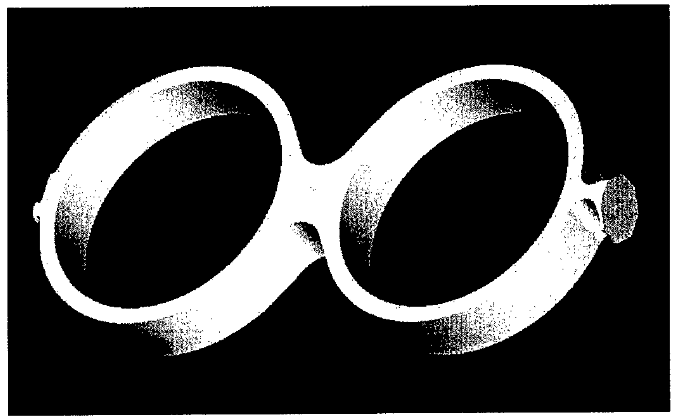

Figure 11: Solid model of the resonator used to drive the focal plane mirror. The mirror is attached to the nub on the right. A magnet is fixed to the left hand ring. Current driven through an adjacent coil induces the left hand ring to oscillate like a loudspeaker. The motion is mirrored by the right hand ring. The mechanism is supported at the center, which remains stationary.

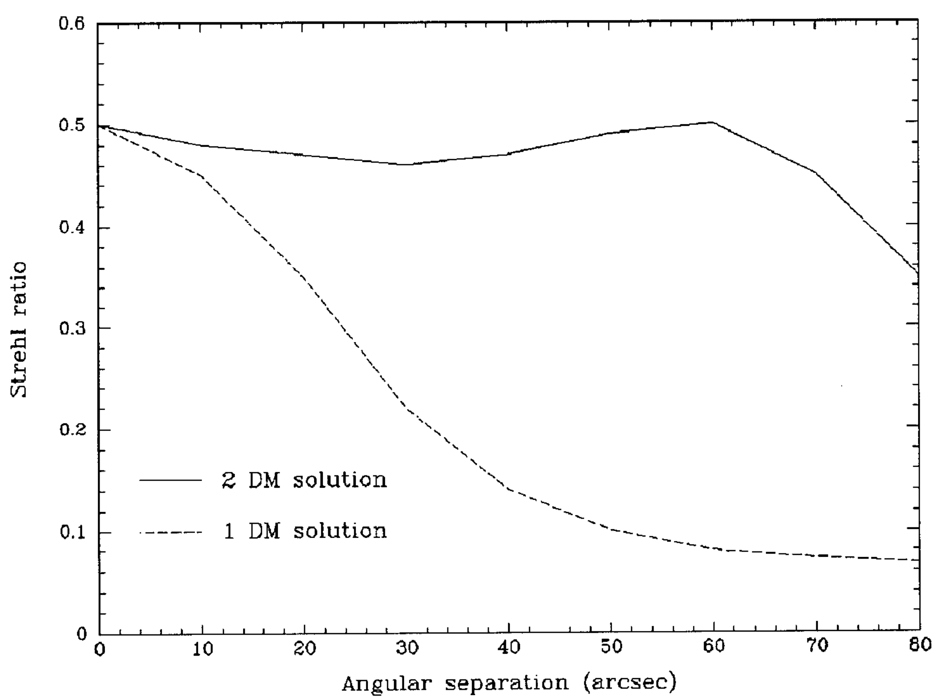

Figure 12: Strehl ratio versus field angle for the cases of a single deformable mirror, and two deformable mirrors, driven on the basis of signals from a ring of five Rayleigh lasers on a 1 arcminute radius. In the case with two DMs, using the tomographic atmospheric analysis, high Strehl ratio is preserved over a large field of view.

7. Other work in progress

7.1 Very High Resolution Visible-Light Spectrograph

With wavefront compensation applied by an AO system, not only is imaging at high spatial resolution possible, but so is high spectral resolution spectroscopy. This high spectral resolution is key to our understanding of the physical processes at work in astronomical events. High resolution spectrographs for visible light have been built in the past, and such instruments have been used to make important discoveries, most notably planets orbiting around other stars. But the addition of AO vastly improves a spectrograph's accuracy and scientific throughput.
An echelle spectrograph with spectral resolution of 200,000 has been constructed that sees simultaneously the entire wavelength range from 400 to 1000 nm, in about 100 spectral orders. The instrument, called the Adaptively Compensated Echelle Spectrograph or ACES, has been commissioned on the 2.5 m Hooker telescope on Mt. Wilson, which incorporates a state-of-the-art AO system providing compensation down to visible wavelengths.

Figure 13 shows a partial spectrum of the star Betelguise (α Ori) recorded during the spectrograph's commissioning. We are currently waiting for assigned time on the 3.5 m adaptive optics telescope at the Starfire Optical Range, Kirtland AFB. The instrument will eventually move to the MMT, where it will take advantage of the HDS to become the most powerful tool for astronomical spectral analysis in the world.

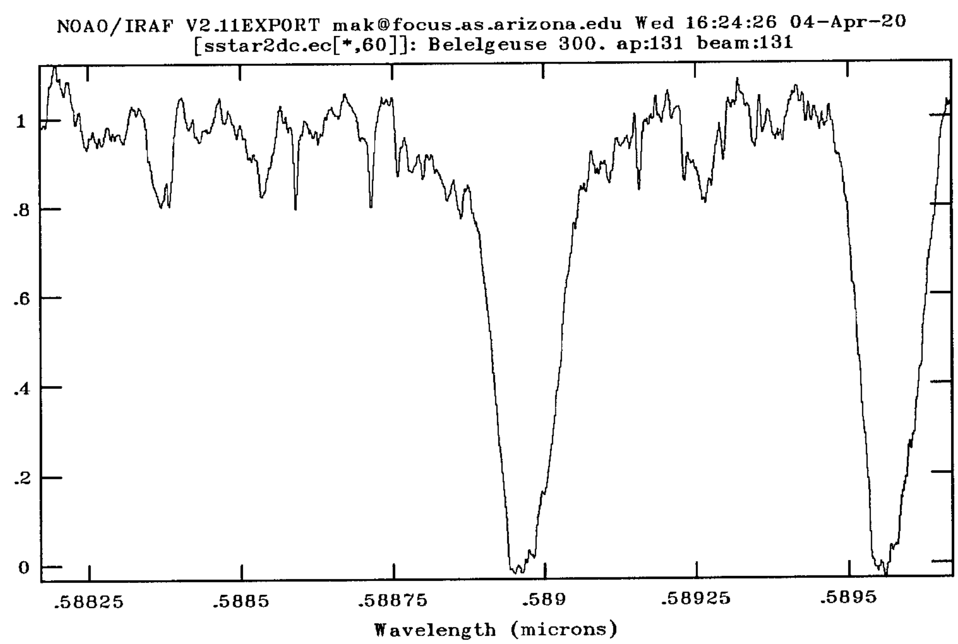

Figure 13: Sodium features in Betelguise spectrum taken with ACES

8. Publications and Outreach

CAAO scientists have been active in participation at internationally attended conferences. Numerous papers (attached to this report) have been presented, with others scheduled for publication in the refereed literature.

The research program continues to attract both graduate and undergraduate students of high caliber. During the grant periods of performance, PhD degrees were awarded to a growing list of scientists.

Two other PhD students from the departments of Astronomy and Optical Sciences are currently doing research projects with the adaptive optics group.

A visiting scholar program implemented along with the program provided an excellent source of visibility for CAAO within the international community. Positions have been filled by Swiss, French and Italian scholars and engineers, who have developed critical elements of the adaptive system including the algorithms required for dynamic control of the AO system and high density deformable mirrors for visible-light compensation We continue to receive requests from interested scholars in Europe, China, and South Korea.

Table 3: Graduates of the UA Adaptive Optics Program

PhD Recipient	Year Graduated	Present Employer
Troy Rhoadarmer	1999	Air Force Starfire Adaptive Optics Facility
Major Robert Johnson	2001	Air Force Starfire Adaptive Optics Facility
Thomas Roberts	2001	Jet Propulsion Laboratory
Philip Hinz	2001	University of Arizona
Maud Langlois	2001	Durham University
Rhonda Morgan	2001	Jet Propulsion Laboratory

As the optics community has become aware of our expertise in adaptive optics, and our work on lightweight deformable optics, interest from industry has strengthened. We are currently discussing plans with a number of major companies to exploit the technology developed at CAAO for industrial application. We expect to develop systems for improved satellite tracking, and for power beaming to geosynchronous communications satellites.

9. Bibliography

The following is a list of papers generated by the CAAO faculty and scholars directly and indirectly supported by the AFOSR grants.

Refereed Papers:

2000

*The Large-aperture Synoptic Survey Telescope (Anthony Tyson and Roger Angel) New Era of Wide-Field Astronomy, ASP Conference Series, 2001, in press.

*Wavefront Sensing with Time-of-Flight Phase Diversity, (Michael Lloyd-Hart, Stuart Jefferies, Roger Angel, and Keith Hege), Optics Letters, in press.

*Thermal Performance Enhancement of Adaptive Optics by use of a Deformable Secondary Mirror, (M. Lloyd Hart) Publications of the Astronomical Society of the Pacific, 112, 264-272, 2000.

1999

*Verification of a System to Prevent Aircraft Illumination by Adaptive Optics Laser Beacons (Michael Lloyd-Hart, Matthew Cheselka, and Robert Hanson) Publications of the Astronomical Society of the Pacific, 112, 264-272, 2000.

1998

*Full Adaptive Optics Images of Asteroids Ceres and Vesta; Rotational Poles and Triaxial Ellipsoid DImensions (Jack D. Drummond, Robert Q. Fugate, Julian C. Christou, and E. Keith Hege);*Icarus,* **132**, 80-99, 1998.

*Search for Life in Other Solar Systems (Roger Angel and Neville J. Woolf); *Scientific American Presents*, **9, #1,** 22-25, Spring 1998.

*Astronomical Searches for Earth-like Planets and Signs of Life (Neville Woolf and J. Roger Angel); *Annual Review of Astronomy and Astrophysics*, **36**, 507-537, 1998.

*Imaging Circumstellar Environments with a Nulling Interferometer (Phillip M. Hinz, J. Roger P. Angel, William F. Hoffman, Donald W. McCarthy Jr., Patrick C. McGuire, Matt Cheselka, Joseph L. Hora, Neville J. Woolf); *Nature*, **395**, 251-253, 1998.

*First Astronomical Images Sharpened with Adaptive Optics Using a Sodium Laser Guide Star (M. Lloyd-Hart, J. R. P. Angel, T. D. Groesbeck, T. Martinez, B. P. Jacobsen, B. A. McLeod, D. W. McCarthy, E. J. Hooper, E. K. Hege, and D. G. Sandler); *ApJ,* **493**, 950-954, 1998.

*The Range of Masses and Periods Explored by Radial Velocity Searches for Planetary Companions (A. F. Nelson and J. R. P. Angel); *ApJ*, **500**, 940-957, 1998.

BOOK CHAPTERS:

1999

*Adaptive Optics: Neural Network Wavefront Sensing, Reconstruction, and Prediction (P.C. McGuire, D.G. Sandler, M. Lloyd-Hart, and T.A. Rhoadarmer) *Scientific Applications of Neural Nets*, Lecture Notes in Physics (Springer, Heidelberg, 1999), Eds. J.W. Clark, T. Lindenau, & M.L. Ristig, pp.97-138.

CONFERENCE PROCEEDINGS:

2001

*Planetary Systems in the Universe: Observation Formation and Evolution (N.J. Woolf, J.R.P. Angel and J.I. Lunine), ASP Conference Series: In Press, A.J. Penny, P Artymowicz, A-M Lagrange and S.S. Russell eds.

2000

*Flat membrane mirrors for space telescopes (B. Stamper, R. Angel, J. Burge, and N. Woolf) Imaging Technology and Telescopes, J. Breckinridge, ed., Proc. SPIE 4013, 2000.

*Novel Optical Systems Design and Optimization III, J. M. Sasian, ed., Proc. SPIE 4092, 2000.

*The Large-aperture Synoptic Survery Telescope (Anthony Tyson and Roger Angel) New Era of Wide-Field Astronomy, ASP Conference Series, 2001, in press.

*Dynamics Refocus for Rayleigh Beams, Science with LBT, Tom Herbst, ed., July 2000, in press.

*BLINC: a testbed for nulling interferometry in the thermal infrared (Philip Hinz, Roger Angel, Nick Woolf, Bill Hoffmann, Don McCarthy) SPIE Conference on Interferometry in Optical Astronomy, eds. Pierre J. Lena, and Andreas Quirrenbach, 4006, Munich, 2000.

*Cryogenic beam-combiner for very low background, 2-20 micron interferometry on the 22.8 m Large Binocular Telescope (D. W. McCarthy, E. Sabatke, R. Sarlot, P. Hinz, and J. Burge) ibid.

*The Dark Matter Telescope (J. Anthony Tyson, David M. Wittman, and J. Roger P. Angel) DM2000 Conference Proceedings, Springer, 2000.

*Adaptive Optics High Resolution Spectroscopy: Present Status and Future Direction (J. Ge, D. Ciarlo, P. Kumenko, C. Alcock, B. Macintosh, K. Cook, C. Max, R. Angel, N. Woolf, M. Lloyd-Hart, and J. Najita) Imaging the Universe in Three Dimensions: Astrophysics with Advanced Multi-Wavelength Imaging Devices, ASP Conference Series, ed. W. van Bruegel & J. Bland-Hawthorn, 2000.

*Prime Focus Coma Corrector for the MMT with "Off the Shelf" Components (M. P. Langlois, J. R. P. Angel, and M. Lloyd-Hart) SPIE Conference on Optical and IR Instrumentation and Detectors, ed. M. Iye and A. F. Moorwood, 4008, Munich, 2000.

Design and realization of ancillary control loops for the MMT adaptive optics system. (George Z. Angeli, Bruce C. Fitz-Patrick, Michael Lloyd-Hart) SPIE Conference on Telescope Structures, Enclosures, Controls, Assembly/Integration/Validation, and Commissioning, eds. Thomas A. Sebring, and Torben Andersen, 4004, Munich 2000.

*Adaptive Optics at the 6.5 m MMT. (M. Lloyd-Hart, F. Wildi, H. Martin, P. McGuire, M. Kenworthy, R. Johnson, B. Fitz-Patrick, G. Angeli, S. Miller, R. Angel) SPIE Conference on Adaptive Optics Systems and Technology, ed. P. Wizinowich, 4007, 167-174, Munich, 2000.

*Adaptive Secondary Mirror for the 6.5 m Conversion of the Multiple Mirror Telescope: Delivery Test Results (A. Riccardi, G. Brusa, V. Bilotti, C. Del Vecchio, P. Salinari, P. Stefanini, P. Mantegazza, R. Biasi, M. Andrighettoni, C. Franchini, D. Gallieni, M. Lloyd-Hart, P. McGuire, S. Miller, and H. Martin) ibid., 524-531.

*Self-Interacting Dark Matter. (B.D. Wandelt, R. Dave, D.N. Spergel, P.J. Steinhardt, P.C. McGuire) Proceedings of the 4th International Symposium on Sources and Detection of Dark Matter/Energy in the Universe, Marina del Rey, California, 2000, in press.

*Stretched membrane with electrostatic curvature (SMEC): A new technology for ultra-lightweight space telescopes. (Roger Angel, James Burge, Keith Hege, Matthew Kenworthy, and Neville Woolf) SPIE Proceedings, UV, Optical, and IR Space Telescopes and Instruments. eds. James B. Breckinridge and Peter Jakobsen, 4013, 699-705, Munich, 2000.

*NGST OTA Optical Metrology Instrumentations and Conceptual Approaches <9R. Keski-Kuha, P. Bely, R. Burg, J. Burge, P. Davila, J. Geary, J. Hagopian, D. Jacobson, A. Lowman, S. Macenka, J. Mangus, C. Perrygo, D. Redding, B. Saif, S. Smith, J. Wyant) ibid., 826-835.

*HST to HST10X: A Second Revolution in Space Science (Holland C. Ford, J. R. P. Angel, C. J. Burrows, J. A. Morse, J. T. Trauger, D. A. Dufford) ibid., 595-603.

*UltraLITE Glass/Composite Hybrid Mirror (Brian Catanzaro, Dan Keane, Steve Connell, Dave Baiocchi, Jim Burge, Arup Maji, Mike Powers) ibid, 663-671.

*Active mirror technology for large space telescopes (J. H. Burge, B. Cuerden, J. R. P. Angel) ibid., 640-648.

*Measurement of Atmospheric Turbulence with a Shack-Hartmann Wavefront Sensor at the new MMT's Prime Focus (P.C. McGuire, M.P. Langlois, M. Lloyd-Hart, T.A. Rhoadarmer, J.R.P.Angel) SPIE Conference on Adaptive Optics Systems and Technology, ed. P. Wizinowich, 4007, 713-716, Munich, 2000.

*Linear Zonal Atmospheric Prediction of Atmospheric Turbulence (P.C. McGuire, T.A. Rhoadarmer, H. Coy, J.R.P. Angel, M. Lloyd-Hart) SPIE Conference on Adaptive Optics Systems and Technology, ed. P. Wizinowich, 4007, 682-691, Munich, 2000.

*Atmospheric Tomography with Rayleigh laser beacons for correction of wide fields and 30 m class telescopes (J.R.P. Angel, M. Lloyd-Hart) SPIE Conference on Adaptive Optics Systems and Technology, ed. P. Wizinowich, 4007, 270-276, Munich, 2000.

*New approach to Rayleigh guide beacons (M. Lloyd-Hart, S.M. Jefferies, E.K. Hege, J.R.P. Angel) SPIE Conference on Adaptive Optics Systems and Technology, ed. P. Wizinowich, 4007, 277-283, Munich, 2000.

*Design for an 8 m telescope with a 3 degree field at f/1.25 - the Dark Matter Telescope (Roger Angel, Michael Lesser, Roland Sarlot, Edward Dunham) ASP Conference Series: Imaging the Universe in Three Dimensions: Astrophysics with Advanced Multi-wavelength Imaging Devices, eds. W. Bruegel and J. Bland-Hawthorn, 195, 81-93, Walnut Creek, 2000.

*Imaging Extra-solar Systems from the Ground: The MMT and LBT Nulling Interferometers (Philip M. Hinz, J. Roger P. Angel, Neville J. Woolf, William F. Hoffmann, and Donald W. McCarthy, Jr.) ASP Conference Series: Working on the Fringe, An International Conference on Optical and IR Interferometry from the Ground and Space, eds. S. Unwin and B. Stachnik, 194, 401-407, Dana Point, 2000.

*Flat mirror optics to study extra-solar terrestrial planets from space (Roger Angel, Jim Burge, and Neville Woolf) ibid, 389-395.

1999

*The adaptive secondary mirror for the 6.5m conversion of the Multiple Mirror Telescope: first laboratory testing results (G. Brusa, A. Riccardi, V. Biliotti, C. Del Vecchio, P. Salinari, P. Stefanini, P. Mantegazza, R. Biasi, M. Andrighettoni, C. Franchini, D. Gallieni) SPIE Conference on Adaptive Optics Systems and Technology, eds. Robert K. Tyson and Robert Q. Fugate, 3762, Denver, 1999

*Object Independent Point Spread Function and Wavefront Phase Estimation (Julian C. Christou, Stuart M. Jefferies, and E. Keith Hege) SPIE Proceedings on Adaptive Optics Systems and Technology, eds. Robert K. Tyson and Robert Q. Fugate, 3762, Denver, 1999.

*Adaptive Optics High Resolution Spectroscopy: Presenet Status and Future Direction (Jian Ge, D. Ciarlo, P Kuzmenko, C. Alcock, B, Macintosh, R. Angel, N. Woolf, M. Lloyd-Hart, R. Q. Fugate, J. Najita) SPIE Proceedings on Adaptive Optics Systems and Technology, eds. Robert K. Tyson and Robert Q. Fugate, 3762, 174-1883, Denver, 1999

*Miniature instrument for the measurement of gap thickness using poly-chromatic interferometry (R.L. Johnson, J.R.P. Angel, M. Lloyd-Hart, and G.Z. Angeli) SPIE Proceedings on Adaptive Optics Systems and Technology, eds. Robert K. Tyson and Robert Q. Fugate, 3762, 245-253, Denver, 1999

*High order adaptive optics system with a high density spherical membrane deformable mirror (M.P. Langlois, J.R.P. Angel, M. Lloyd-Hart, S. Miller, and G. Angeli) SPIE Proceedings on Adaptive Optics Systems and Technology, eds. Robert K. Tyson and Robert Q. Fugate, 3762, 50-57, Denver, 1999

*Full-System Laboratory Testing of the F/15 Deformable Secondary Mirror for the New MMT Adaptive Optics System (P.C. McGuire, M. Lloyd-Hart, J.R.P. Angel, G.Z. Angeli, R.L. Johnson, B.C. Fitzpatrick, W.B. Davison, R.J. Sarlot, C.J. Bresloff, J.M. Hughes, S.M. Miller, P. Schaller, F.P. Wildi, M.A. Kenworthy, R.M. Cordova, M.L.Rademacher, M.H. Rascon, J.H. Burge, B.L. Stamper, C.Zhao, P. Salinari, C.Del Vecchio, A. Riccardi, G.Brusa, R. Biasi, M. Andrighettoni, D. Gallieni, C. Franchini, D.G. Sandler, T.K. Barrett) SPIE Conference on Adaptive Optics Systems and Technology, ed s. R.Q. Fugate and R. K. Tyson, 3762, 28-37, Denver, 1999.

*Construction and Testing of the Wavefront Sensor Camera for the New MMT Adaptive Optics System (P.C. McGuire, T.A. Rhoadarmer, M. Lloyd-Hart, J.C. Shelton, M.P. Lesser, J.R.P. Angel, G.Z. Angeli, J.M. Hughes, B.C. Fitz-Patrick, M.L. Rademacher, P.

Schaller, M.A. Kenworthy, F.P. Wildi, J.G. Capara, D.B. Ouellette) SPIE Conference on Adaptive Optics Systems and Technology, eds. R.Q . Fugate and R. K. Tyson, 3762, 269-282, Denver, 1999.

*Laboratory Adaptive Optics System for Testing the Wavefront Sensor of the New MMT (T.A. Rhoadarmer, P.C. McGuire, J.M. Hughes, M. Lloyd-Hart, J.R.P. Angel, S. Schaller, M.A. Kenworthy) SPIE Conference on Adaptive Optics Systems and Technology, eds. R.Q. Fugate and R. K. Tyson, 3762, 161-173, Denver, 1999.

*Progress report on the optical system for closed-loop testing of the multiple mirror telescope adaptive secondary mirror (Roland J. Sarlot, Cynthia J. Bresloff, James H. Burge, Bruce C. Fitz-Patrick, Patrick C. McGuire, Brian L. Stamper, Chun Yu Zhao) Proc. SPIE 3779, Current Developments in Optical Design and Optical Engineering VIII, Robert E. Fischer, and Warren J. Smith, Eds., July 1999, Denver, CO.

*Optical design of ARIES: the new near infrared science instrument for the adaptive f/15 Multiple Mirror Telescope (Roland J. Sarlot, Donald W. McCarthy, James H. Burge, Jian Ge) Proc. SPIE 3779, Current Developments in Optical Design and Optical Engineering VIII, Robert E. Fischer, and Warren J. Smith, Eds., July 1999, Denver, CO.

*From adaptive secondary mirrors to extra-thin extra-large adaptive primary mirrors (G. Brusa, A. Riccardi, M. Accardo, V. Biliotti, M. Carbillet, C. Del Vecchio, S. Esposito, B. Femenia, O. Feeney, L. Fini, S. Gennari, L. Miglietta, P. Salinari) ESO Proc, Workshop on Extremely Large Telescopes (in press).

*Novel Adaptive Optics System for the 6.5 meter MMT telescope (P. McGuire, M. Lloyd-Hart, R. Angel, G. Angeli, D. McCarthy, T. Rhoadarmer, R. Johnson, T.Roberts, M. Langlois, B. Fitzpatrick, W. Davison, J. Burge, R. Sarlot, J. Hughes, S. Miller, S. Schaller, B. Jacobsen, C. Shelton, P. Salinari, C. Del Vecchio, G. Brusa, R. Biasi, D. Gallieni, D. Sandler, T. Barrett) abstract to the Centennial American Physical Society (APS) Meeting, Atlanta, 1999.

*Extremely Large Space Telescopes and Interferometers made with flat primary mirrors (J. R. P. Angel, J. H. Burge, and N. J. Woolf) Ultra Lightweight Space Optics Challenge Workshop, Napa, CA, March 24-25, 1999.

*Glass membrane mirrors beyond NGST (J.H. Burge, J.R.P. Angel, B. Cuerden, N.J. Woolf) Ultra Lightweight Space Optics Challenge Workshop, Napa, CA, March 24-25, 1999.

*A linear micro-processing actuator for ambient and cryogenic operation (Brian Cuerden and Roger Angel) Ultra Lightweight Space Optics Challenge Workshop, Napa, CA, March 24-25, 1999.

*Refining Nulling Interferometry with the Old and New Multiple Mirror Telescope (P.M. Hinz, J.R.P. Angel, W.F. Hoffman, D.W. McCarthy, N.J. Woolf, P.C. McGuire) abstract to the 193rd American Astronomical Society Meeting, Austin, Texas, January 1999.

1998

*PSF calibration in astronomical imaging -- physical constraints for a noisy problem (E.K. Hege) in OSA Tech. Digest Signal Recovery and Synthesis VI, Kona HI, June 1998.

*Space object identification using a physically-constrained iterative deconvolution algorithm (J.C. Christou, E.K. Hege, S.M. Jefferies and B. Jeffs) ibid, p20-22, 1998.

*Astronomical results using a physically-constrained iterative deconvolution algorithm (E.K. Hege, M. Cheselka, M. Lloyd-hart, P. Hinz, W.F. Hoffmann, J.C. Christou and S.M Jefferies) ibid, p23-25, 1998.

*Real-time adaptive optimization of wavefront reconstruction algorithms for closed-loop adaptive-optical systems (B.L. Ellerbroek and T.A. Rhoadarmer) *Adaptive Optical System Technologies*, ed. D. Bonaccini and R.K. Tyson, Proc. SPIE **3353**, 1174-1185, 1998.

*Adaptive secondary mirror for the 6.5 m MMT (T.K. Barrett, D.G. Bruns, T.J. Brinkley, D.G. Sandler, B.C. Fitzpatrick, J.R.P. Angel, T. Rhoadarmer) *Adaptive Optical System Technologies*, ed. D. Bonaccini and R.K. Tyson, Proc. SPIE **3353**, 754-763, 1998.

*Infrared adaptive optics system for the 6.5 m MMT: system status (M. Lloyd-Hart, G. Angeli, R. Angel, P. McGuire, T. Rhoadarmer, and S. Miller) Presented at the ESO topical meeting on *Astronomy with Adaptive Optics-Present Results and Future Programs*, Garching bei Munchen, September 7-11, 1998.

*Astronomical results using a physically-constrained iterative deconvolution algorithm (E.K. Hege, M. Cheselka, M. Lloyd-Hart, P. Hinz, W.F. Hoffman, J.C. Christou, and S.M. Jefferie s) OSA Conference on *Signal Recovery and Synthesis*, Kona, 1998.

*Optical system for closed-loop testing of adaptive optic convex mirror (R.J. Sarlot, J.H. Burge) SPIE annual meeting, San Diego, July 1998.

*Verifying Mirror Technology for NGST with a Space-Qualified, Cryogenic 3.5 m Mirror (Roger Angel and Jim Burge) To be published in ESA Conference Proceedings, *"Workshop on the Next Generation of Space Telescope: Science Drivers & Technical Challenges,"* ed. B. Kaldeich, Liege, Belgium, June 15-18, 1998.

*Sensitivity of Nulling Interferometers to Extra-solar Zodiacal Emission (EZE) (Roger Angel) *Exozodiacal Dust Workshop*, eds. D. E. Backman, L. J. Caroff, S. A. Sandford, and D. H. Wooden, **NASA/CP 1998-10155**, 209-218, 1998.

*Interferometry with the Large Binocular Telescope (J. Roger P. Angel, J. M. Hill, P. A. Strittmatter, P. Salinari, Gerd Weigelt) Proc. SPIE on *Astronomical Interferometry*, eds. R. D. Reasenberg and J. B. Breckinridge, **3350**, 881-889, Kona, HI, 1998.

*Planet Discoverer Interferometer I: PDI, a potential precursor to Terrestrial Planet Finder (N. J. Woolf, J. R. P. Angel, C. A. Beichman, J. Burge, M. Shao, and D. Tenerelli) ibid., p. 683-689.

*First results of nulling interferometry with the Mulitiple Mirror Telescope (P. M. Hinz, J. R. P. Angel, W. F. Hoffman, D. W. McCarthy Jr., P. C. McGuire, M. Cheselka, J. L. Hora, and N. J. Woolf) ibid., p. 439-447.

*Interferometric capability for the Magellan Project (N. P. Carleton, W. A. Traub, and J. R. P. Angel) ibid., 733-735.

*Toward NGST (Roger Angel, Jim Burge, and Neville Woolf) SPIE Proc. on *Space Telescopes and Instruments V*, eds. P. Y. Bely and J. B. Breckinridge, **3356**, 185-186, Kona, HI, 1998.

*Lightweight mirror technology using a thin facesheet with active rigid support (J. H. Burge, J. R. P. Angel, B. Cuerden, H. M. Martin, S. M. Miller, D. G. Sandler) ibid., p. 690-701.

*Casting the First 8.4 meter Boroscilicate Honeycomb Mirror for the Large Binocular Telescope (J. M. Hill, J. R. P. Angel, R. D. Lutz, B. H. Olbert, and P. A. Strittmatter) SPIE Proc. on *Advanced Technology Optical/IR Telescopes VI*, ed. L. M. Strepp, **3352**, 172-181, Kona, HI, 1998.

*Infrared Adaptive Optics System for the 6.5 m MMT: System Status and Prototype Results (M. Lloyd-Hart, R. Angel, D. Sandler, T. Barrett, P. McGuire, T. Rhoadarmer, D. Bruns, S. Miller, D. McCarthy, and Matt Cheselka) SPIE Proc. on *Adaptive Optical System Technologies*, eds. D. Bonaccini and R. K. Tyson, **3353**, 82-93, Kona, HI, 1998.

*Simultaneous Measurements of Sodium Column Density and Laser Guide Star Brightness (Jian Ge, B. P. Jacobsen, J. R. P. Angel, P. C. McGuire, T. Roberts, B. McLeod, M. Lloyd-Hart) ibid., p. 242-253.

*Thermal Characterization of the Support Plate for the 6.5 m MMT Thin-shell, Adaptive-secondary Mirror (T. A. Rhoadarmer, M. Lloyd-Hart, B. Fitz-Patrick, M. Rademacher, D. G. Bruns, and C. Shelton) ibid., p. 826-836.

*Solid-State Raman Laser for MMT Sodium Guide Star (W. T. Roberts Jr., James T. Murray, W. L. Austin, Richard C. Powell, J. Roger P. Angel) ibid., p. 347-355.

*Design of the First Generation Wave Front sensor and Actuator Geometry for the 6.5 m MMT Adaptive-optical System (T. A. Rhoadarmer, P. C. McGuire, M. Lloyd-Hart, J. R. P. Angel, B. Cuerden, B. Fitz-Patrick, D. G. Sandler) ibid., p. 579-590.
*Adaptive Secondary Mirror for the 6.5-m MMT (T. K. Barrett, D. G. Bruns, T. J. Brinkley, D. G. Sandler) ibid., p. 2-11.

*Alluminum Reference Plate, Heat Sink, and Actuator Design for an Adaptive Secondary Mirror (C. Del Vecchio) ibid., p. 839-849.

*High Order Adaptive Secondary Mirrors: Where Are We? (Piero Salinari and Dave G. Sandler) ibid., p. 742-753.

*Adaptive Secondary P30 Prototype: Laboratory Results (G. Brusa, A. Riccardi, S. Ragland, S. Esposito, C. Del Vecchio, L. Fini, P. Stefanni, V. Biliotti, P. Ranfagni, P. Salinari, D. Gallieni, R. Biasi, P. Mantegazza, G. Sciocco, G. Noviello, and S. Invernizzi) ibid., p. 764-775.

*MMT Adaptive Secondary Prototype Development (Roberto Biasi, Daniele Gallieni) ibid., p. 858-863.

*Control Electronics for an Adaptive Secondary Mirror (Roberto Biasi, Luca Fini, Paolo Mantegazza, Valdemaro Bilotti, Federico Gori, Daniele Gallieni) ibid., p. 1193-1201.

*High Frequency Wavefront structure and its effects on the detection of faint companions using adaptive optics (M. Langlois, D. Sandler, P. Ryan, and D. McCarthy) ibid., p. 189-200.

*Optical Spectroscopy with a Near Single Mode Fiber Feed and Adaptive Optics (Jian Ge, Roger Angel, Chris Shelton) Proc. on *Optical Astronomical Instrumentation*, **3355**, 353-363, Kona, HI, 1998.

*Sensitivity of an Active Space Telescope to Faint Sources and Extra-solar Planets (Roger Angel and Neville Woolf) *"Science with the Next Generation Space Telescope,* ed. Eric Smith and Anuradha Koreans, Astronomical Society of the Pacific Conference Series **133**, 172-187, 1998.

*Large ground-based telescopes with high order adaptive optics for imaging faint objects and extra-solar planets (M. Langlois, D. Sandler, and D. McCarthy), NATO Summer School, Cargese, May 1998